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13. SUPPLEMENTARY NOTES

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14. ABSTRACT

Using a novel harmonic balance method and a state of the art computational fluid dynamics (CFD) model, limit cycle oscillations have been calculated for a conventional and supercritical airfoil as well as the F-16 wing. The latter result is the first of its kind.

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FINAL TECHNICAL REPORT
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
THEORETICAL PREDICITON OF LIMIT CYCLE OSCILLATIONS IN SUPPORT OF FLIGHT FLUTTER TESTING

AFOSR GRANT NUMBER F49620-01-1-0148

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Principal Investigator
Department of Mechanical Engineering and Materials Science
School of Engineering, Duke University, Durham, N.C.

December 31, 2003

We have done a wide-ranging parameter study for the typical section airfoil including the effects of plunge to pitch frequency ratio, mass ratio and Mach number. These calculations were done by exercising our reduced order modeling capability to obtain the many flutter points required much more rapidly than would be the case using conventional methods. This work has now been extended to the calculation of limit cycle oscillations (LCO) to show the effects of the same parameters. At the moment we are concentrating on the determination of LCO due to aerodynamic nonlinearities.

The results obtained are quite interesting and show the following effects.

1) There can be a change in LCO due to aerodynamic nonlinearities from benign to dangerous as the Mach number is changed. By benign LCO we mean no LCO below the nominal flutter speed and by dangerous LCO we mean LCO can occur below the nominal linear flutter speed.

2) Our results for LCO including viscous effects in the aerodynamic model, are being compared to experiment. Initial results are promising.

3) The above LCO calculations have now been extended to 3D inviscid flow. Current work is directed toward adding the effects of viscosity to the 3D flow model.

We have submitted two abstracts to the 2003 AIAA SDM conference that cover items 1-2 above and another paper is to be presented at the ASME International Congress this fall discussing Item 3.

Attached is a copy of the presentation presented at the AFOSR T&E Meeting in June 2003 summarizing our work to date. Among the most significant results are the first predictions of Limit Cycle Oscillations for the F-16 aircraft due to aerodynamic nonlinearity.

THEORETICAL PREDICTION OF LIMIT CYCLE OSCILLATIONS

Earl Dowell
Duke University

AFOSR TEST AND EVALUATION PROGRAM
South Lake Tahoe, California
June 4-5, 2003

KEY T&E CENTER CONTACT: DR. CHARLES DENEGRI
SEEK EAGLE OFFICE, EGLIN AFB

PROGRESS TO DATE

- DEVELOPMENT OF RAPID & ACCURATE CFD MODELS

  DETERMINATION OF FLUTTER BOUNDARIES AND LIMIT CYCLE OSCILLATIONS

  * 2D,INVISCID
  * 2D, VISCOUS
  * 3D,INVISCID
  * 3D, VISCOUS

- APPLICATIONS TO

  * SUPERCRITICAL AIRFOIL, NLR 7301 (VISCOUS)
  * AGARD WING, 445.6 (VISCOUS)
  * F-16 WING (INVISCID)

PLANS FOR NEXT YEAR

- METHODS DEVELOPMENT: EXTENSION TO WING PLUS STORES
- APPLICATIONS TO
    - * F-16 WING (VISCOUS)
    - * F-16 WING PLUS STORES (INVISCID)
    - * MAVRIC WING (INVISCID)

RESULTS TRANSITIONED TO T&E CENTER

- F-16 RESULTS
- RAPID AND ACCURATE CFD CODES (PENDING)

PUBLICATIONS

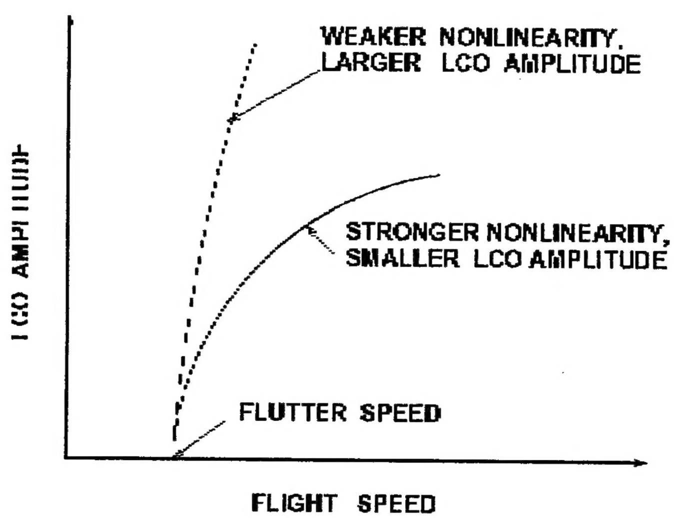
THOMAS, J. P. , DOWELL, E. H. AND HALL, K.C., "NONLINEAR INVISCID AERODYNAMIC EFFECTS ON TRANSONIC DIVERGENCE, FLUTTER AND LIMIT CYCLE OSCILLATIONS," AIAA JOURNAL, VOL. 40, NO. 4, 2002, PP. 638-646.

THOMAS, J. P. , DOWELL, E.H., AND HALL, K.C., "A HARMONIC BALANCE APPROACH FOR MODELING THREE-DIMENSIONAL NONLINEAR UNSTEADY AERODYNAMICS AND AEROELASTICITY," ASME PAPER IMECE-2002-32532, PROCEEDINGS OF THE ASME INTERNATIONAL MECHANICAL ENGINEERING CONFERENCE AND EXPOSITION, NOVEMBER 17-22, 2002, NEW ORLEANS, LA.

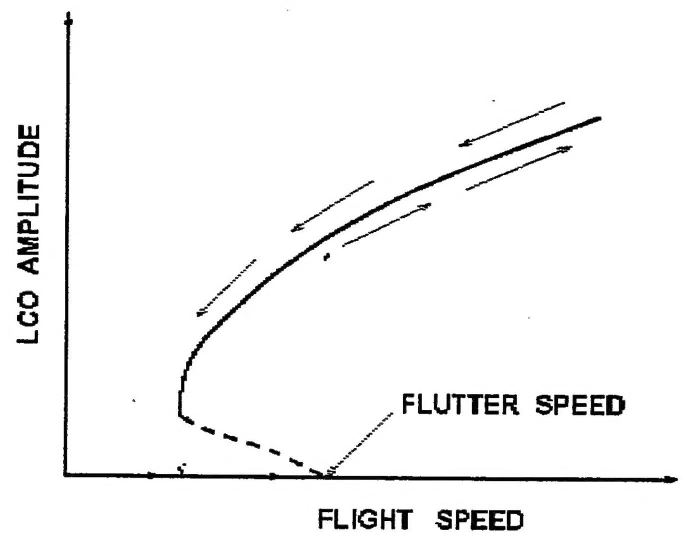
THOMAS, J. P., HALL, K. C. AND DOWELL, E. H., "A HARMONIC BALANCE APPROACH FOR MODELING NONLINEAR AEROELASTIC BEHAVIOR OF WINGS IN TRANSONIC FLOW," AIAA PAPER-2003-1924, PRESENTED AT THE 44TH AIAA/ASME/ADCE/AHS/ASC STRUCTURES, STRUCTURAL DYNAMICS AND MATERIALS CONFERENCE AND EXHIBIT, APRIL 7-10, 2003, NORFOLK, VA.

SCHEMATIC OF LIMIT CYCLE OSCILLATION RESPONSE

"Good" Nonlinearity



"Bad" Nonlinearity



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THE SEVERAL PHYSICAL SOURCES OF NONLINEARITIES

STRUCTURE

- CONTROL SURFACE FREE-PLAY (SUBCRITICAL & VERY STRONG)
- WING-STORE FREE-PLAY (?)
- PLATE-LIKE STIFFNESS (SUPERCRITICAL & STRONG)
- VERY HIGH ASPECT RATIO WING (SUBCRITICAL & MODERATELY STRONG)

FLUID (OUR FOCUS TODAY)

- SHOCKWAVES (SUB OR SUPERCIRTICAL & WEAK USUALLY, BUT MAY BE STRONG)
- SEPARATED FLOW (SUB OR SUPERCRITICAL & STRONGER)

LCO DUE TO AERODYNAMIC NONLINEARITIES

- SHOCKWAVES
- SEPARATED FLOW

ACCURATE, EFFECTIVE AND EFFICIENT COMPUTATIONAL METHODS: THREE IMPORTANT IDEAS

1. FIRST DETERMINE A NONLINEAR STATIC STATE OF THE SYSTEM, THEN CONSIDER SMALL (LINEAR) DYNAMIC PERTURBATION ABOUT THAT STATIC STATE, E.G. A NONLINEAR STEADY FLOW WITH SHOCKS AND/OR FLOW SEPARATION. THE "LOCAL" (IN PHASE SPACE) SYSTEM STABILITY MAY THEN BE DETERMINED.

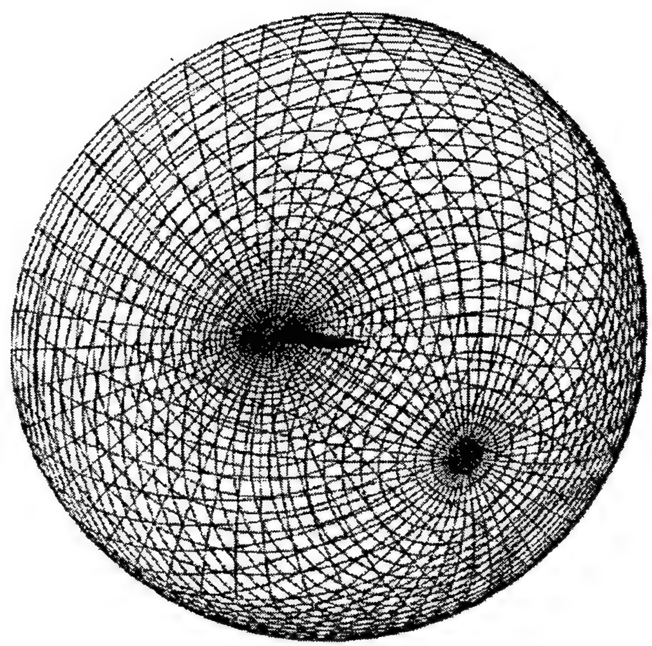
2. FOR A NONLINEAR, DYNAMIC MODEL EXPAND THE SOLUTION IN A FOURIER SERIES IN TIME AND RETAIN ONLY A FEW HARMONICS. THIS IS NORMALLY SUFFICIENT TO DETERMINE LIMIT CYCLE OSCILLATIONS OF FLUID-STRUCTURAL SYSTEMS.

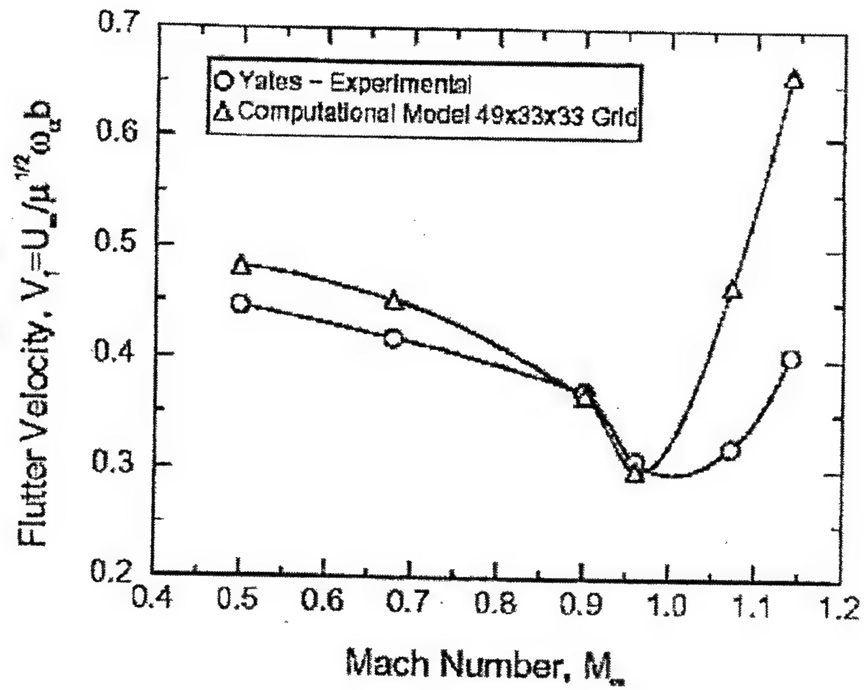
   - COMPUTATIONAL COST OF (1) OR (2) IS COMPARABLE TO THAT OF THE NONLINEAR STATIC OR STEADY FLOW SOLUTION.

3. EXPAND SOLUTION IN TERMS OF GLOBAL MODES FOR STRUCTURE AND FLUID.

   - COMPUTATIONAL COST OF (3) IS USUALLY REDUCED BY SEVERAL ORDERS OF MAGNITUDE OVER THAT OF A SOLUTION BASED UPON A MODEL USING GENERALIZED COORDINATES ON LOCAL SPATIAL GRIDS.

Accomplishments – New Scientific Findings
HB flutter solution of a 3D AGARD 445.6 wing





Correlates well with experimental measurements at M < 1

ZONA TECHNOLOGY

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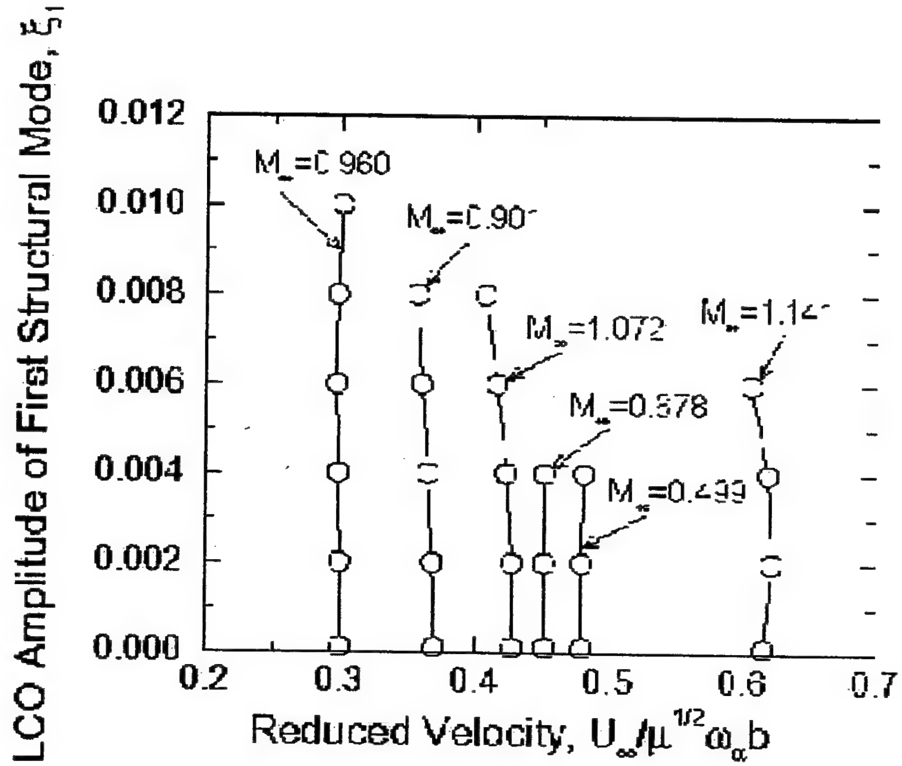
ACCOMPLISHMENTS – NEW SCIENTIFIC FINDINGS
HB FLUTTER SOLUTION OF A 3D AGARD 445.6 WING



PREDICTS AN UNSTABLE LCO IN LOW SUPERSONIC MACH NUMBER RANGE. LCO OF LARGE AMPLITUDE MAY BE ENCOUNTERED *BELOW* THE PREDICTED FLUTTER BOUNDARY

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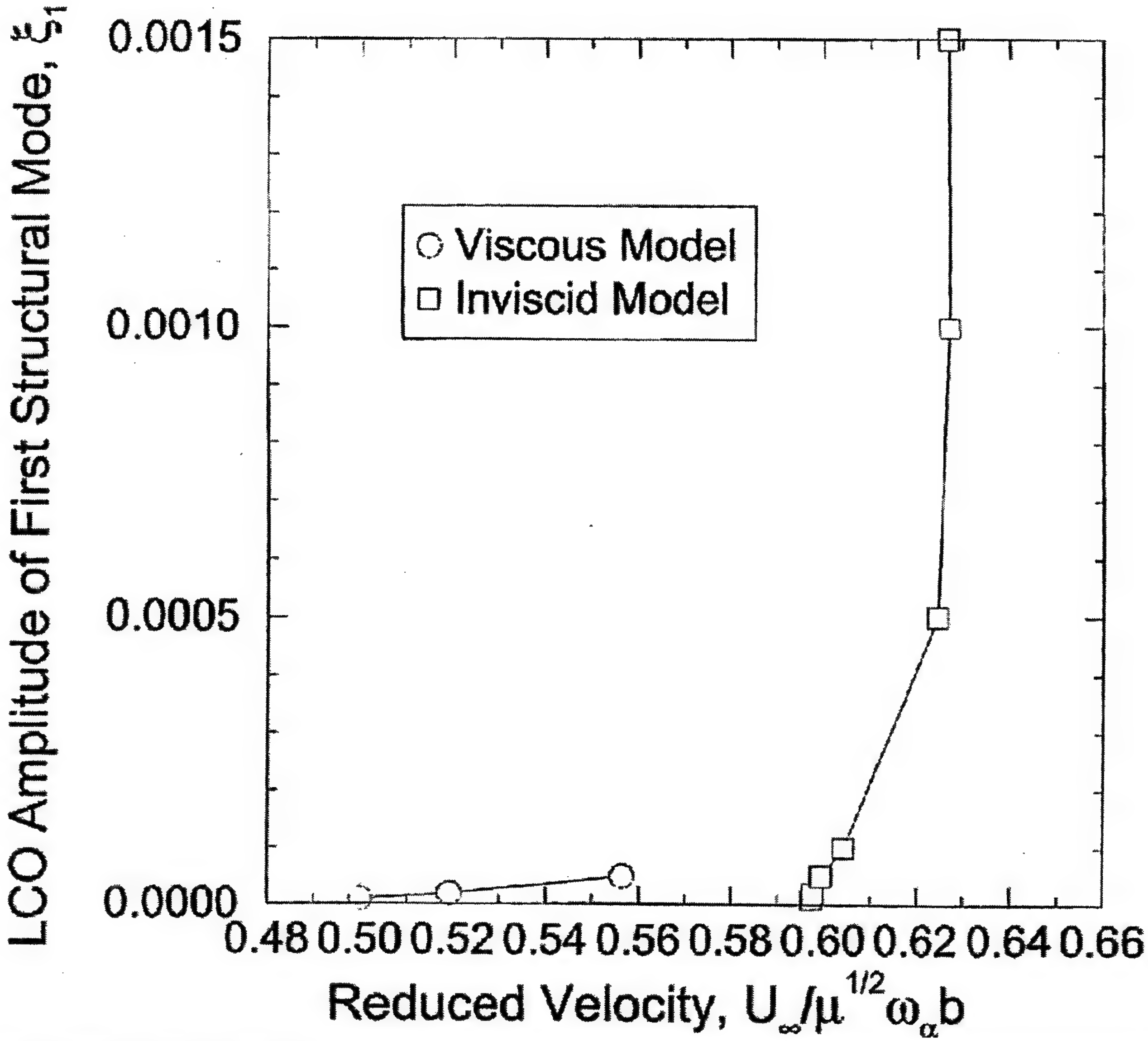
LCO Response Amplitude Vs. Reduced Velocity



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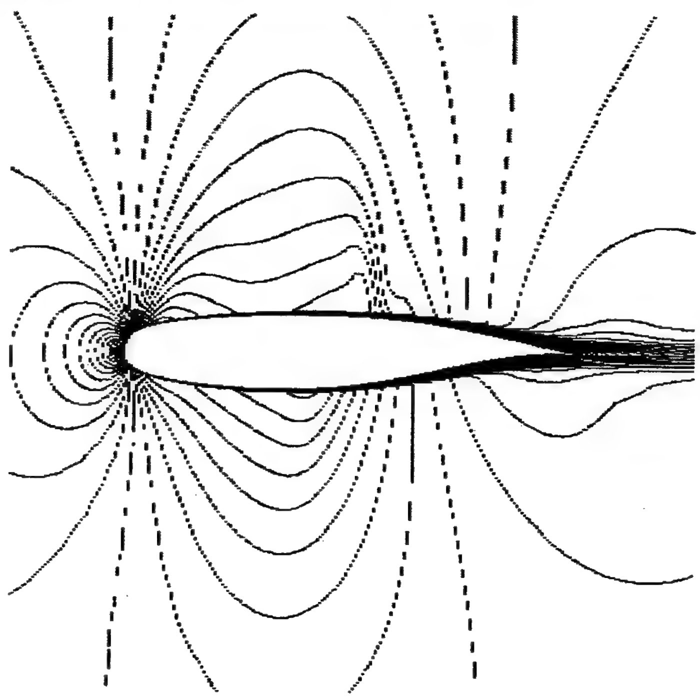
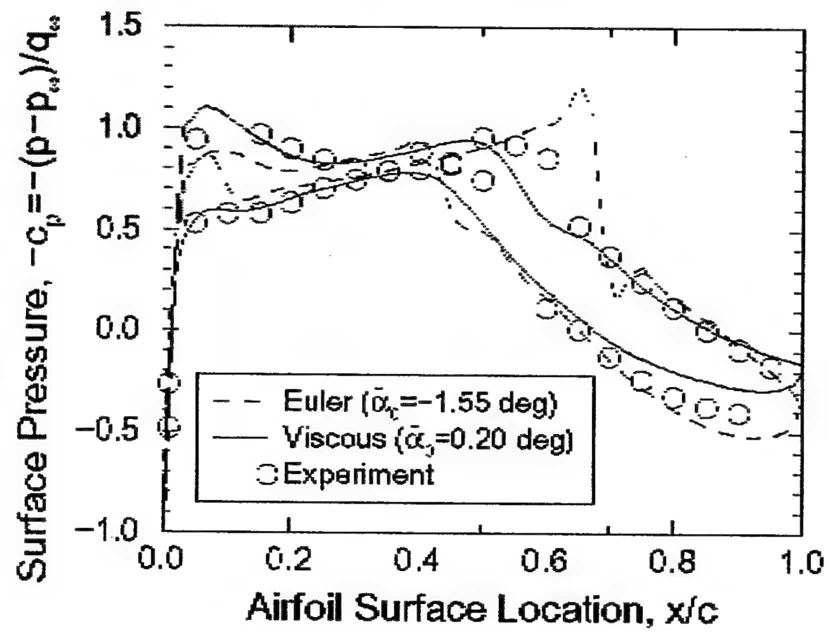
VISCOUS TRANSONIC AIRFOIL AEROELASTIC MODEL NLR 7301 AIRFOIL SECTION

Mach Contours $M_\infty = 0.75$



Surface Pressure Distribution



STEADY FLOW PRESSURE DISTRIBUTION: COMPARISON OF THEORIES AND EXPERIMENT

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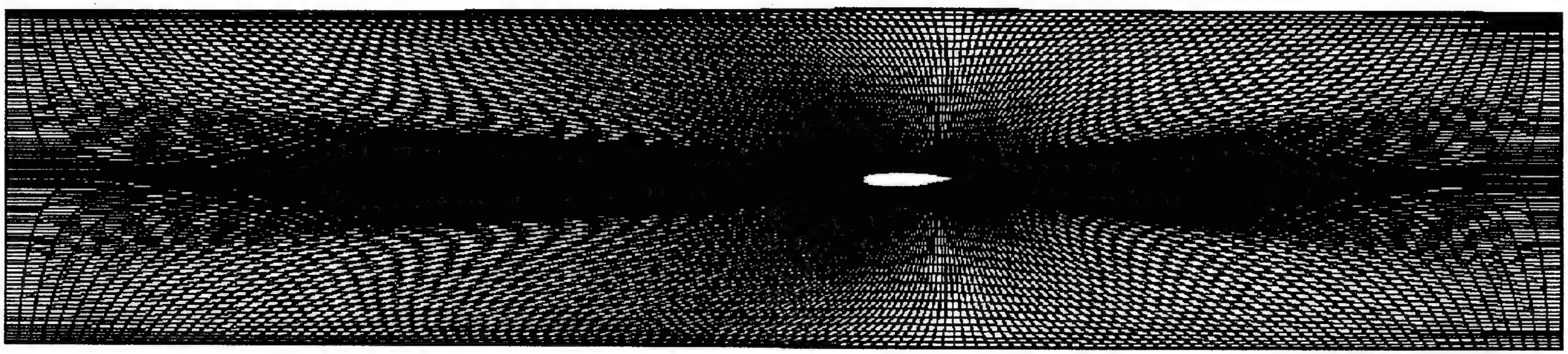
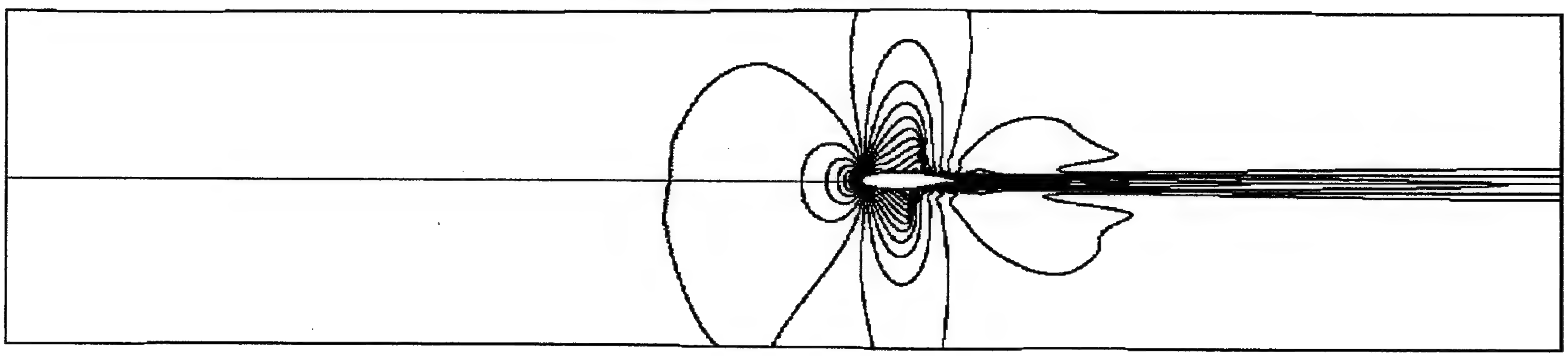
NLR 7301 Airfoil in Wind-Tunnel Test Section
Computational Mesh and Steady Mach Contours

Computational Mesh



Mach Contours



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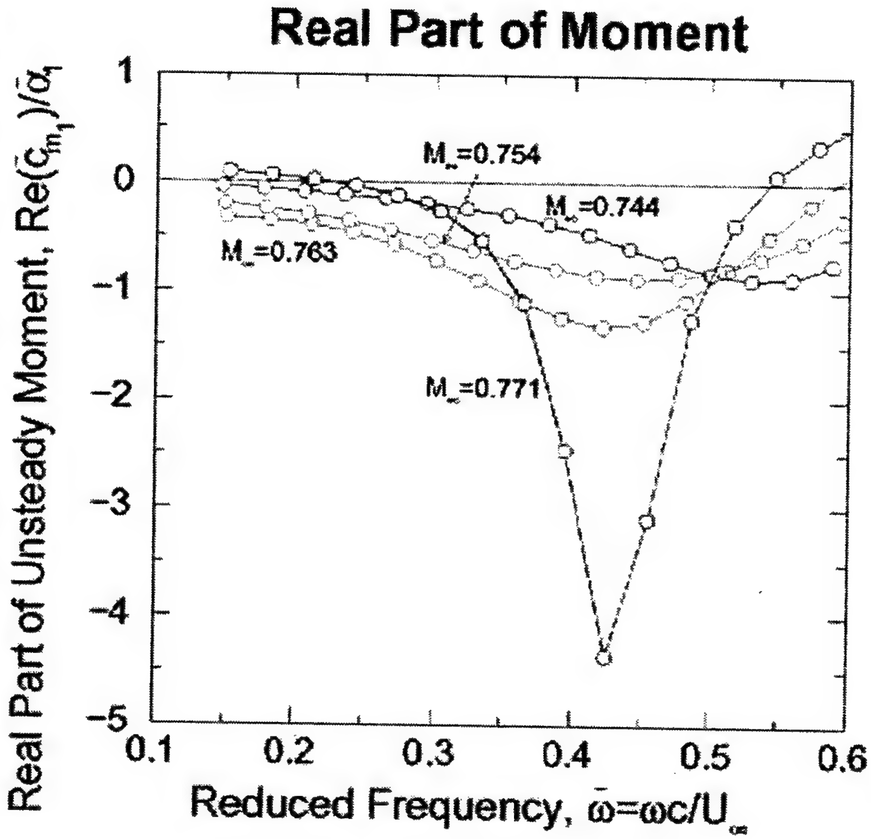
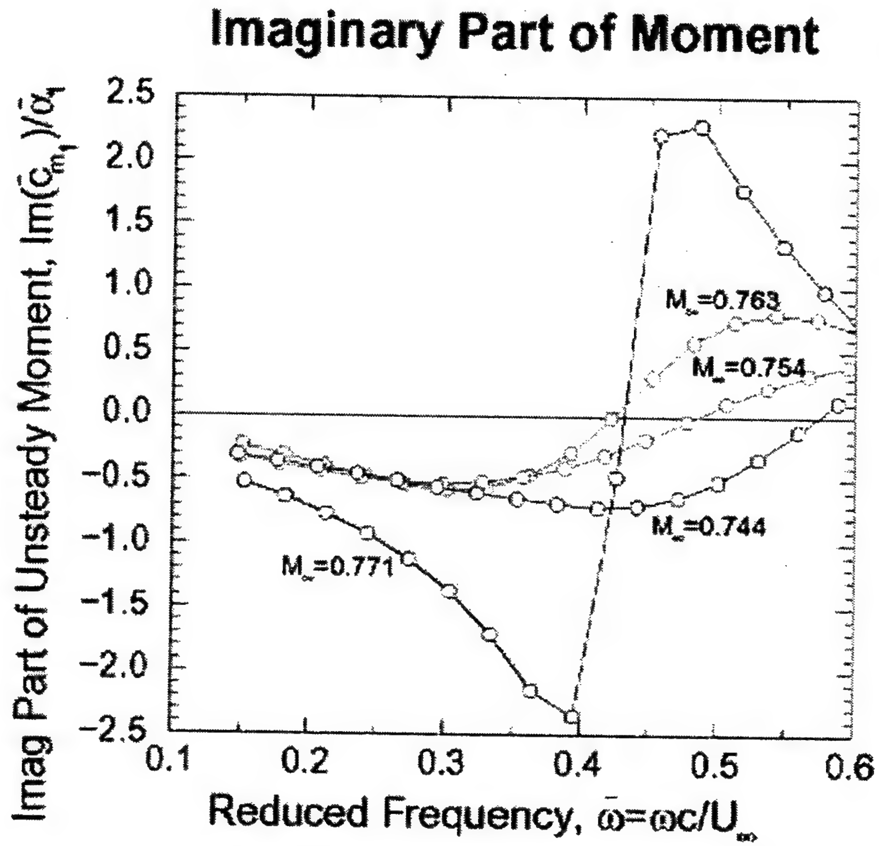
NLR 7301 Airfoil in Wind-Tunnel Test Section
Computed Unsteady Moment Data





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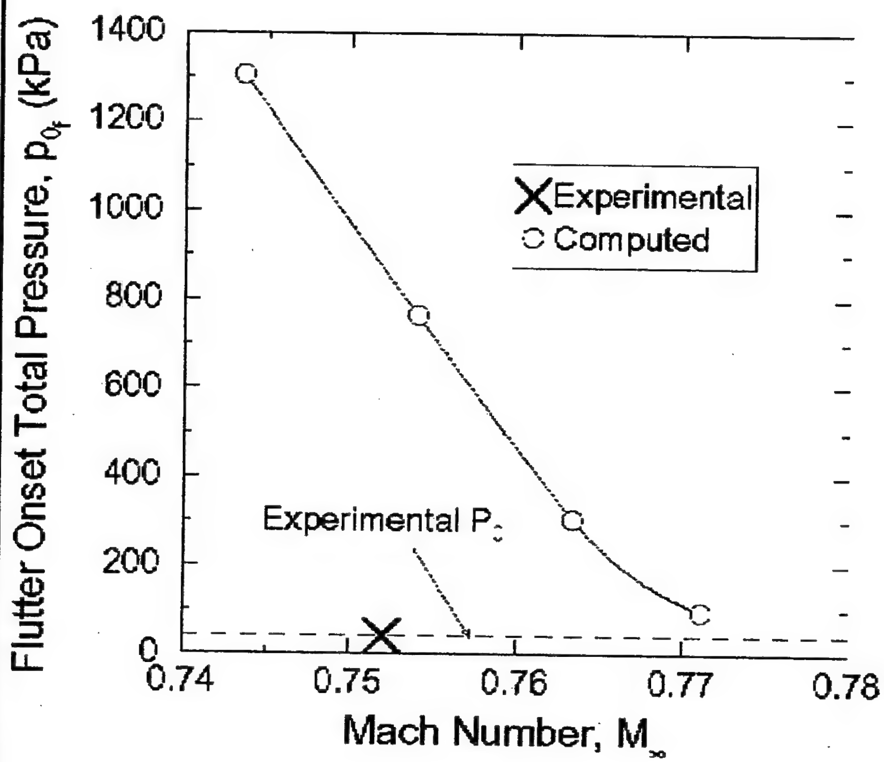
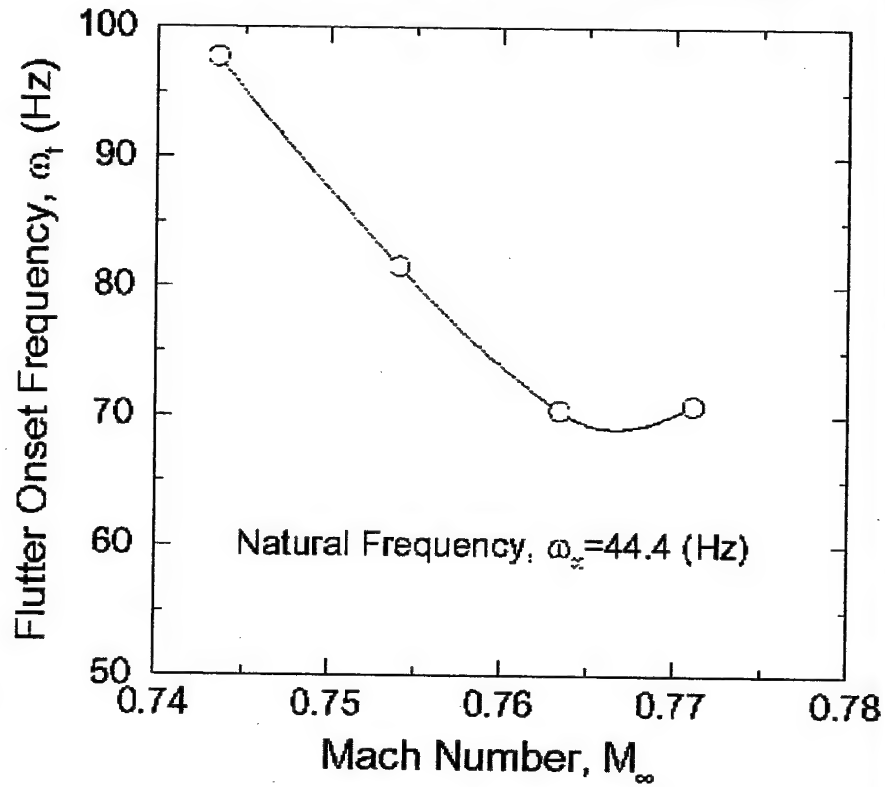
NLR 7301 Airfoil in Wind-Tunnel Test Section
Calculated Single Degree-of-Freedom Flutter Trend

Flutter Onset Total Pressure



Flutter Onset Frequency



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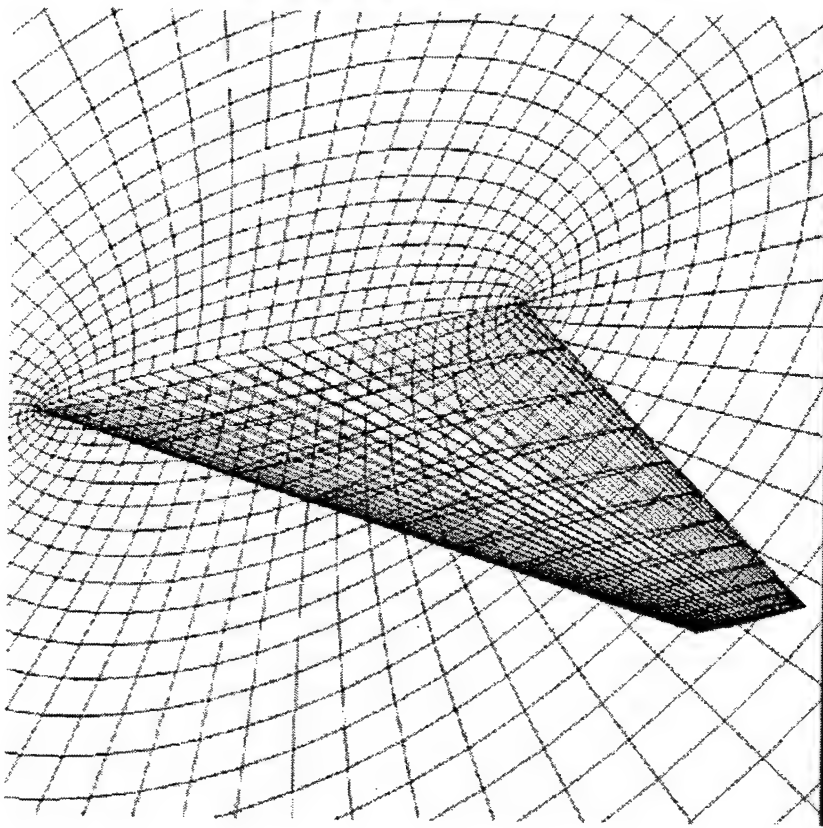
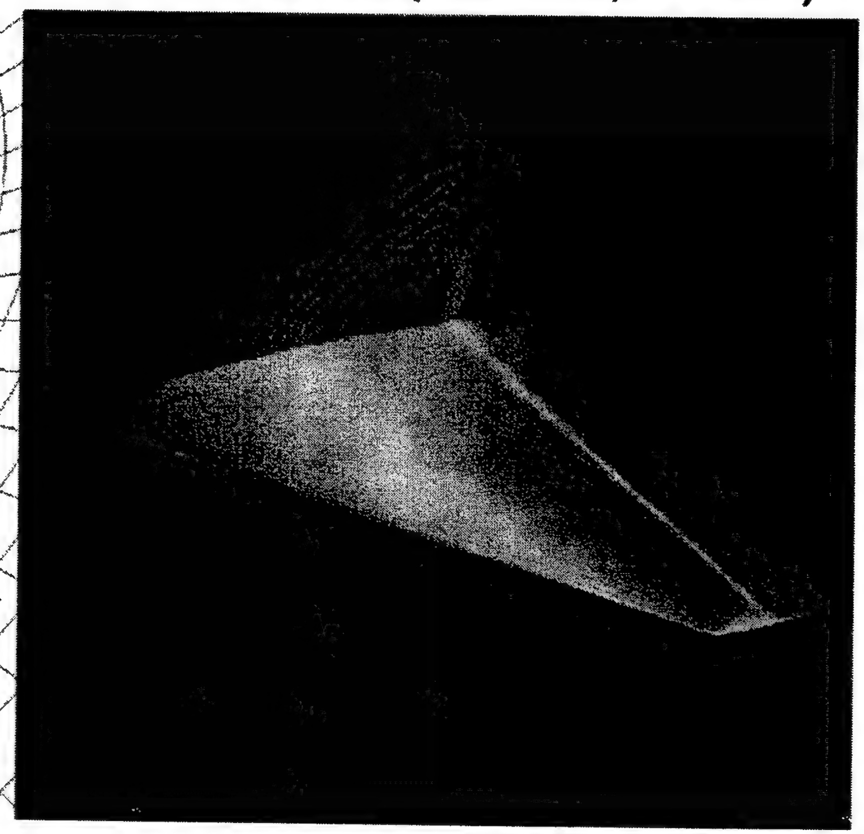
F-16 HB/LCO Nonlinear Aeroelastic Model
Computational Mesh and Steady Flow Solution

Computational Mesh

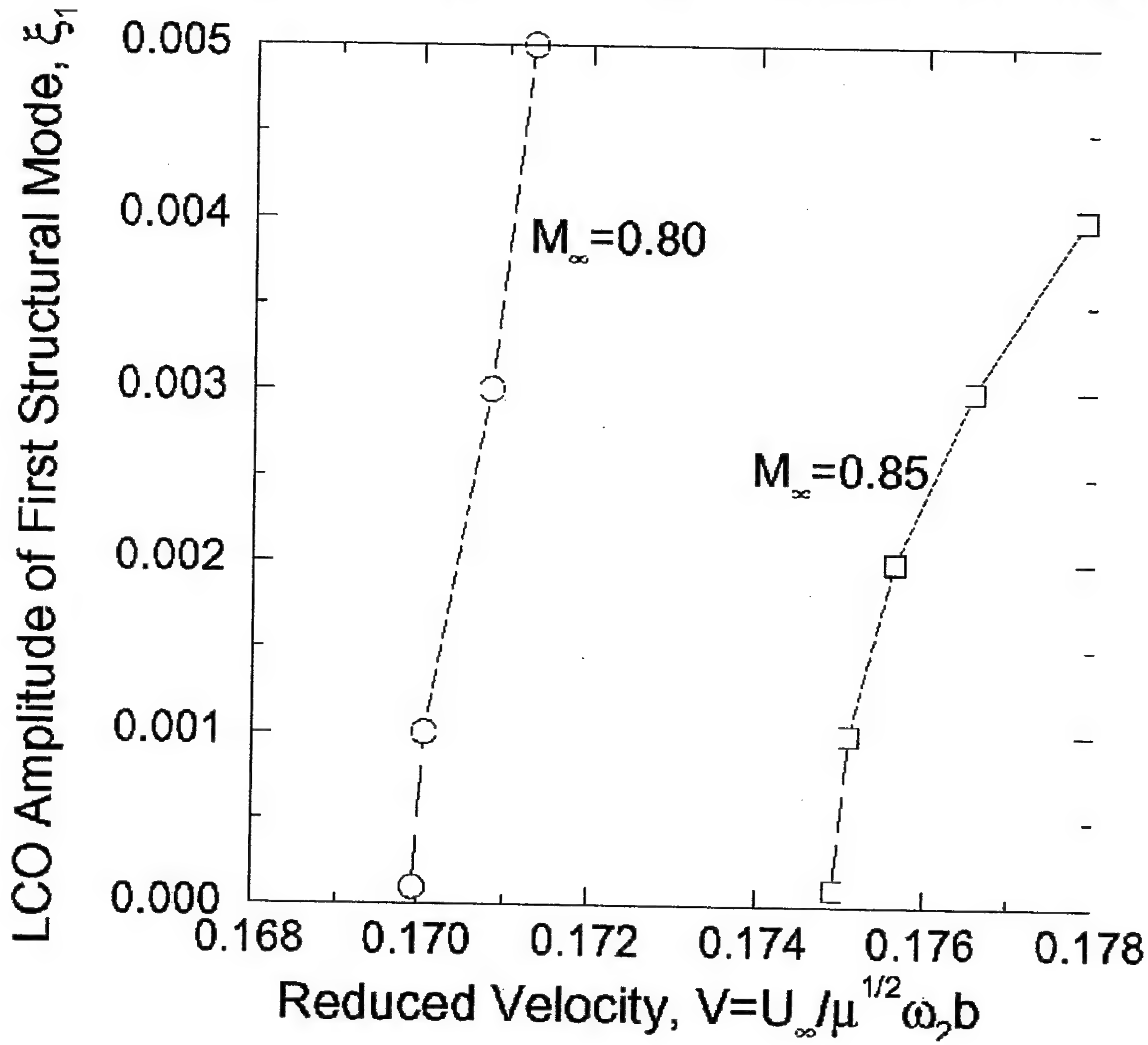


Mach Contours ($M_\infty = 0.9, \alpha = 1.0°$)



F-16 Inviscid LCO Amplitude Response Trend

h=5,000 feet, "Typical LCO" Structural Modes



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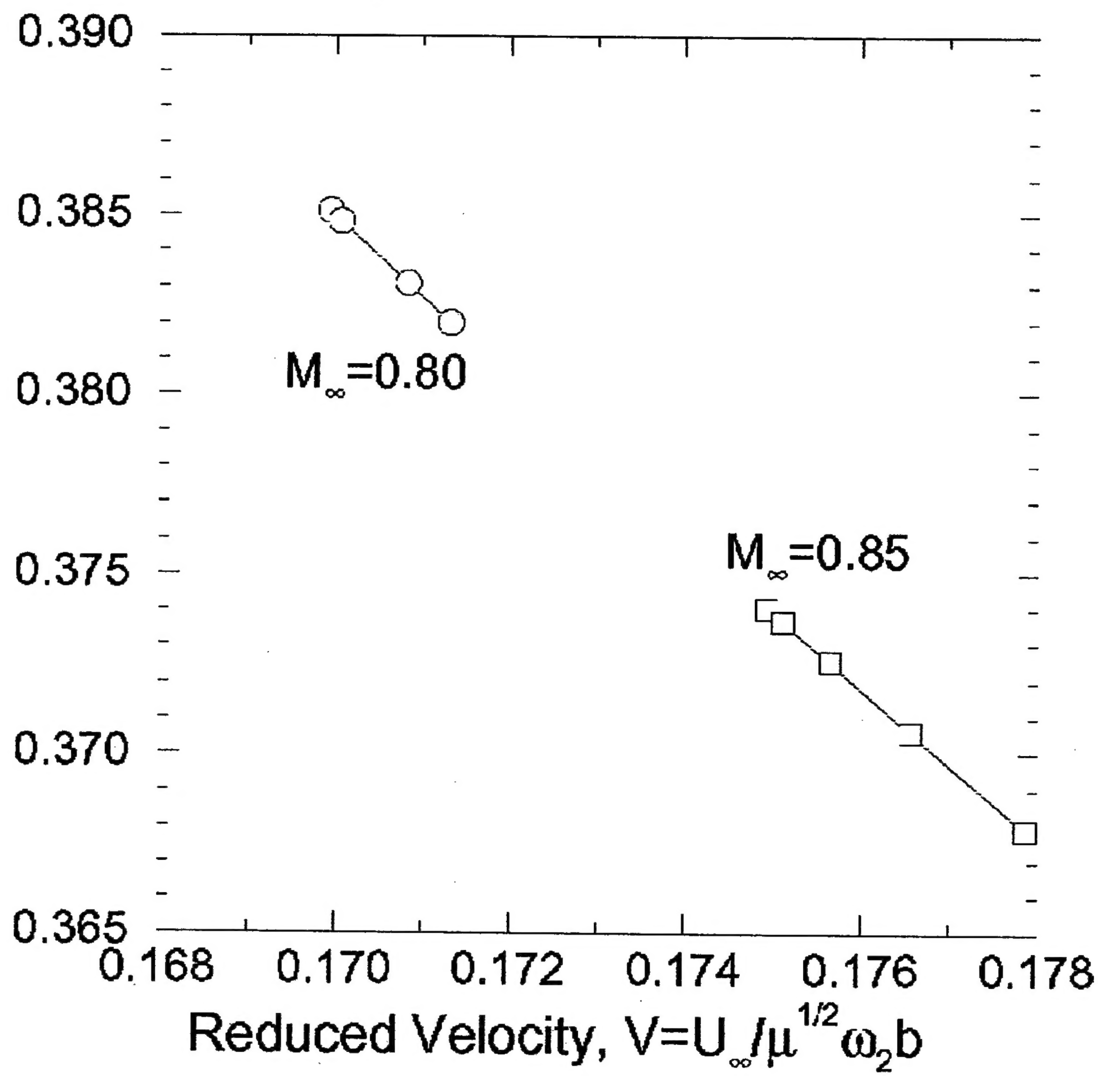
F-16 Inviscid LCO Frequency Response Trend

h=5,000 feet, “Typical LCO” Structural Modes



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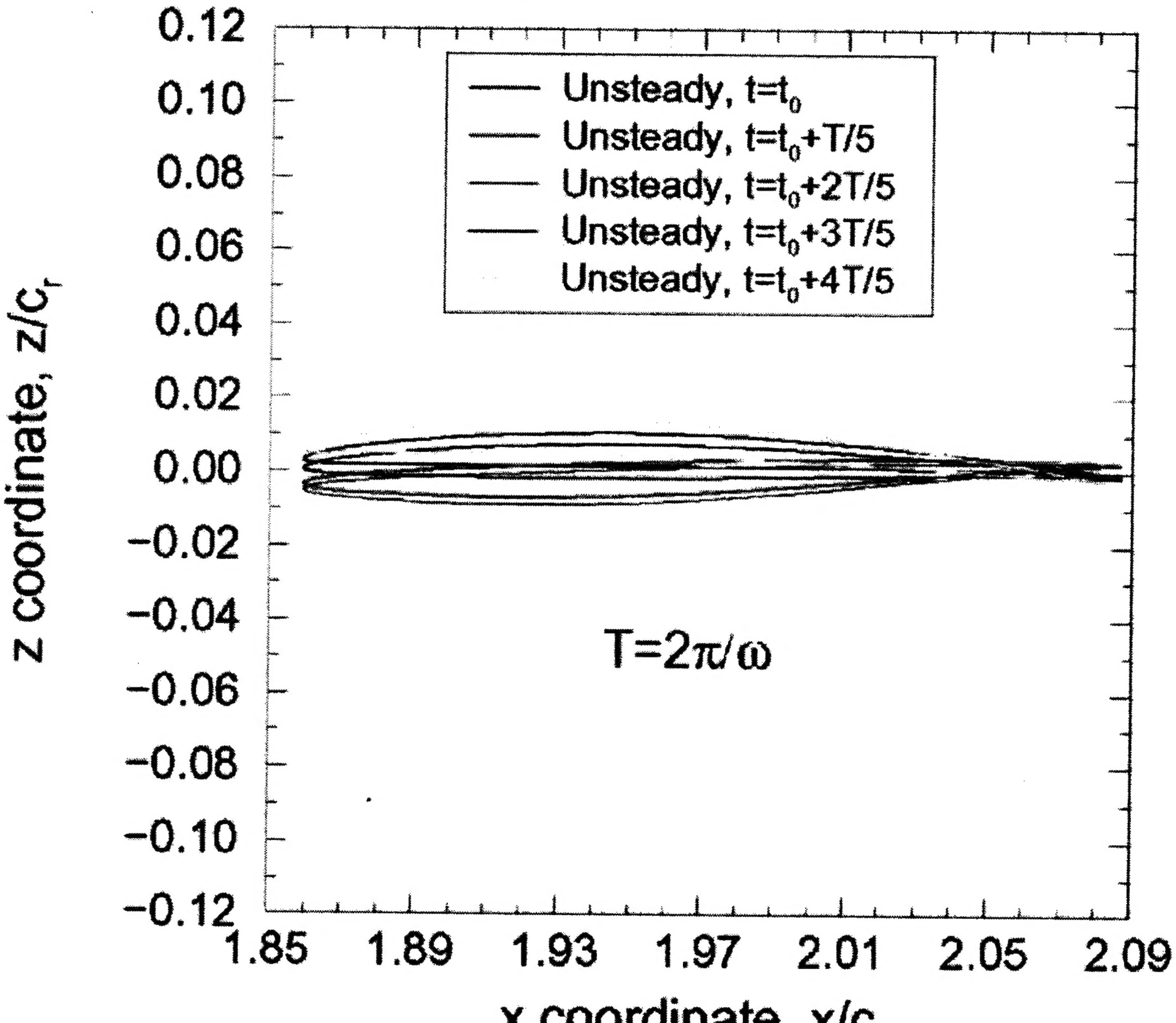
F-16 Inviscid LCO Wing Tip Motion $\xi_1 = 0.004$

M=0.85, h=5,000 feet, "Typical LCO" Structural Mode Shapes



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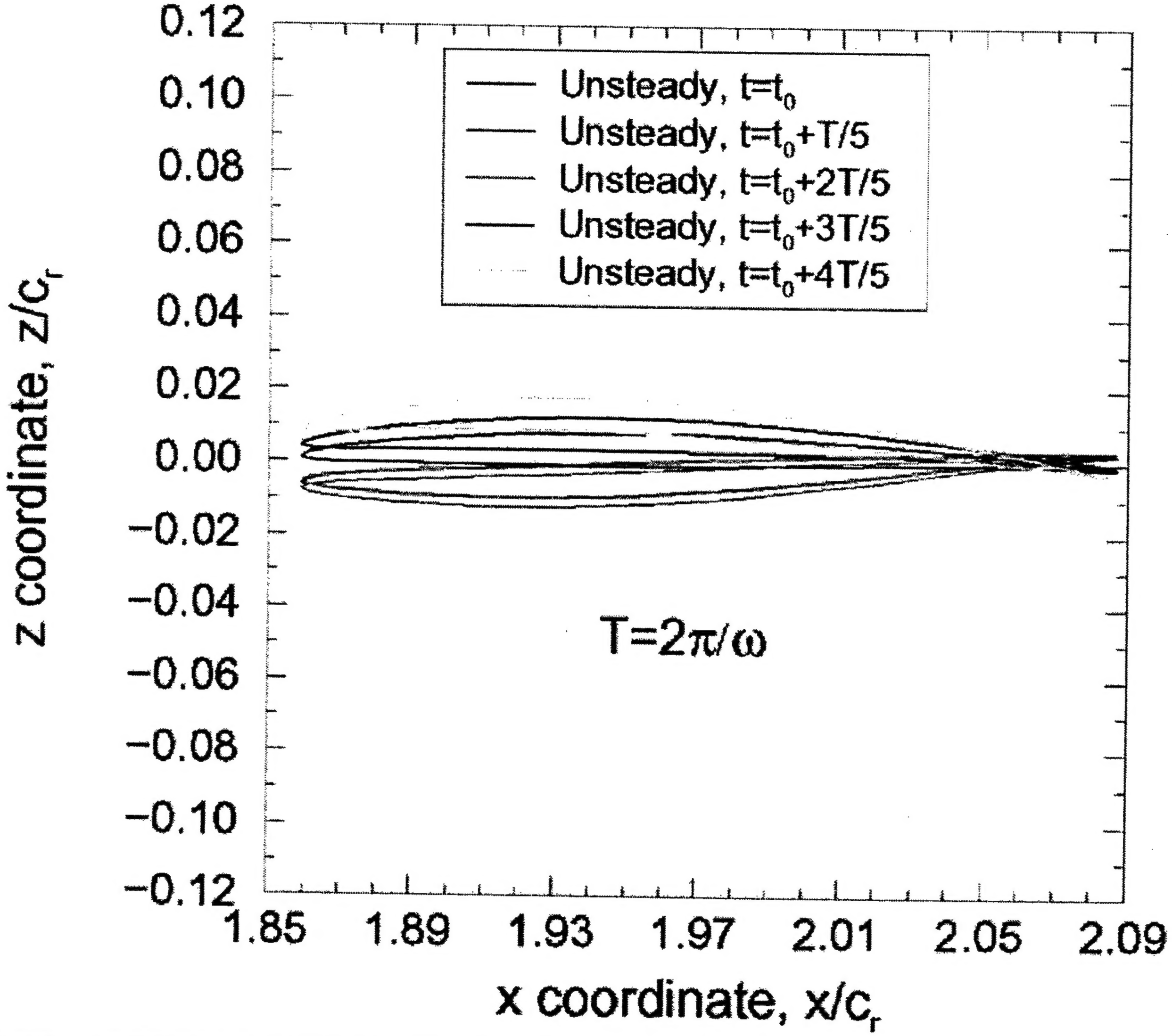
F-16 Inviscid LCO Wing Tip Motion $\xi_1 = 0.005$

M=0.80, h=5,000 feet, "Typical LCO" Structural Mode Shapes



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CONCLUSIONS

- VISCOUS EFFECTS ARE IMPORTANT FOR SUPERCRITICAL AIRFOIL (NLR7301)
- BUT, LCO RESULTS FOR A CONVENTIONAL AIRFOIL (NACA 64A010) SHOW A MUCH SMALLER VISCOUS FLOW EFFECT
- AN EULER (INVISCID) BASED LCO CAPABILITY NOW EXISTS FOR THREE-DIMENSIONAL FLOWS OVER WINGS USING POD/ROM AND HB
- WORK IS UNDERWAY TO EXTEND VISCOUS MODEL TO THREE-DIMENSIONAL FLOW FIELDS
- WIND TUNNEL AND FLIGHT TEST DATA ARE AVAILABLE FOR CORRELATIONS IN THREE-DIMENSIONAL FLOWS / FOCUS OF FUTURE WORK